

DISCOVERY AND MONITORING OF A NEW BLACK HOLE CANDIDATE XTE J1752-223 WITH *RXTE*: RMS SPECTRUM EVOLUTION, BH MASS AND THE SOURCE DISTANCE.

NIKOLAI SHAPOSHNIKOV^{1,2}, CRAIG MARKWARDT², JEAN SWANK² AND HANS KRIMM^{2,3}

Accepted for publication in The Astrophysical Journal 9/09/2010

ABSTRACT

We report on the discovery and monitoring observations of a new galactic black hole candidate XTE J1752-223 by Rossi X-ray Timing Explorer (*RXTE*). The new source appeared on the X-ray sky on October 21 2009 and was active for almost 8 months. Phenomenologically, the source exhibited the low-hard/high-soft spectral state bi-modality and the variability evolution during the state transition that matches standard behavior expected from a stellar mass black hole binary. We model the energy spectrum throughout the outburst using a generic Comptonization model assuming that part of the input soft radiation in the form of a black body spectrum gets reprocessed in the Comptonizing medium. We follow the evolution of fractional root-mean-square (RMS) variability in the *RXTE*/PCA energy band with the source spectral state and conclude that broad band variability is strongly correlated with the source hardness (or Comptonized fraction). We follow changes in the energy distribution of rms variability during the low-hard state and the state transition and find further evidence that variable emission is strongly concentrated in the power-law spectral component. We discuss the implication of our results to the Comptonization regimes during different spectral states. Correlations of spectral and variability properties provide measurements of the BH mass and distance to the source. The spectral-timing correlation scaling technique applied to the *RXTE* observations during the hard-to-soft state transition indicates a mass of the BH in XTE J1752-223 between 8 and 11 solar masses and a distance to the source about 3.5 kiloparsec.

Subject headings: accretion, accretion disks—black hole physics—stars: individual (XTE J1752-223)

1. INTRODUCTION

A black hole (BH) X-ray transient is a binary system in which a stellar mass black hole is orbiting a regular star. During mass exchange episodes that occur when a compact star oblates matter from the normal star a system is seen as a bright X-ray source. This accretion process is accompanied by a plethora of spectral and variability phenomena that are unique to BH candidates and most probably related to a strongly relativistic nature of the compact object. Among the most puzzling aspects of the accreting BH phenomenology is spectral state bi-modality, extended power law spectral tails, aperiodic and quasi-periodic variability. Uncovering the nature of these effects is crucial to advance in different aspects of BH physics. In this Paper we present *Rossi X-ray Timing Explorer* (*RXTE*) observations of a newly discovered BH candidate source XTE J1752-223 during its recent October 2009 - May 2010 outburst. We describe the general evolution of the outburst, correlation of the energy spectral characteristics and variability properties and the changes in the variability distribution with energy. We estimate the BH mass using the correlation scaling technique and address some implication of variability evolution during the observed spectral state transition.

The main feature of the X-ray spectrum observed from an accreting BH is a presence of a strong non-thermal component described by a power law. The origin of

this emission is attributed to multiple inverse Compton scattering of the soft photons off the energetic electrons near the central source. The properties and the balance between the thermal and non-thermal components in the source spectrum is the primary parameter defining a BH spectral state (Remillard & McClintock 2006; Belloni 2005a). The state with a dominant non-thermal emission is called the low-hard state (LHS) due to the fact that it is usually observed during low luminosity episodes during the rise and decay stages of an outburst. During most outbursts BH sources exhibit transitions (intermediate state, IS) to the high-soft state (HSS), dominated by the thermal component, attributed to a geometrically thin accretion disk. Strong (up to 50 percent root-mean-square) aperiodic variability is seen in Fourier Power Density Spectra (PDS) during the LHS in the form of band-limited noise which is flat at low frequencies and a power-law at higher frequencies (alternative names used in literature are flat top noise and white-red noise). The rms fraction of this noise component tends to decrease in intermediate state and is suppressed to a few percent or not detected at all in the HSS. During the LHS and IS quasi-periodic oscillations (QPO) are also present in the PDS. The hard/soft state dichotomy is one of the most puzzling aspects of the accreting stellar mass BH phenomenology. This behavior has a very recognizable pattern (most commonly presented as a famous q-shaped hardness-intensity diagram, see Belloni 2010, for the latest review). It is reproduced in almost all sources and outbursts with a striking level of stability.

There are more than twenty X-ray sources in our galaxy in which optical measurements show BH masses

¹ CRESST/University of Maryland, Department of Astronomy, College Park MD, 20742, nikolai.v.shaposhnikov@nasa.gov

² Goddard Space Flight Center, NASA, Astrophysics Science Division, Greenbelt MD 20771

³ CRESST/Universities Space Research Association, Columbia MD, 21044

higher than the theoretical mass limit for a rotating neutron star (see Remillard & McClintock 2006, for details). These sources are therefore called confirmed BHs. There is also approximately the same number of X-ray binaries for which optical mass measurements are unavailable but which otherwise show properties very similar to the confirmed BHs. These sources are referred to as BH candidates. Better knowledge of the BH population is important for understanding some aspects of stellar evolution. In this Paper we present BH mass and distance measurements for XTE J1752-223 using the correlation scaling method. Shaposhnikov & Titarchuk (2009, hereafter ST09) have shown that correlations during state transitions can be used to estimate BH mass and source distance. The scaling method relies on the theoretically motivated and observationally tested assumption that the QPO frequency for a particular accretion state of the system is set by the BH mass. Information on the spectrum normalization allows us also to estimate the distance to the source. During our monitoring program with *RXTE* we were able to observe a part of the LHS-to-HSS transition, which provided sufficient data to apply the scaling method to XTE J1752-223. The scaling method yields for XTE J1752-223 the BH mass of $\sim 9.5 M_{\odot}$ and the distance of about 3.5 kpc.

The main goal of this Paper is to present the evolution of X-ray properties during the XTE J1752-223 discovery outburst observed with *RXTE* and to report the mass and distance estimates of the compact object based on the spectral and variability correlation scaling method. We analyzed all *RXTE* observations taken during the outburst active phase. We follow the properties of the energy spectrum by applying a Comptonization model to the data. We also characterize the variability properties by examining periodic and aperiodic features in the Fourier Power Density Spectrum. We also analyze the energy dependence of the variability and its evolution during the LHS-to-HSS state transition. Specifically, we find strong evidence that fast (less than 100 sec) aperiodic variability is almost completely confined to the power-law spectral component, while the black body component introduces no significant variability. The observed distribution of variability within the non-thermal part of the X-ray emission, i.e. a steep decrease of variability amplitude with energy, has important implications for the physics of photon up-scattering in the accreting BHs.

The paper is structured as follows. In the next section we describe the discovery observation with *RXTE*/PCA bulge scans. Details of our data analysis are presented in §3. In §4 we present the general evolution of the source as observed by with *RXTE* and *Swift*, and uncover the source evolution through BH spectral states. In §5 we present analysis of the energy dependence of the variability and its evolution with the source spectral states. Mass measurements and distance estimates with *RXTE* data using the scaling technique are described in §6. In §7 we discuss the source behavior and possible implications of our observational results for the accretion regimes in BHs during different spectral states and transitions between them. Conclusions follow in §8.

2. DISCOVERY AND IDENTIFICATION OF XTE J1752-223 AS A NEW GALACTIC BH CANDIDATE

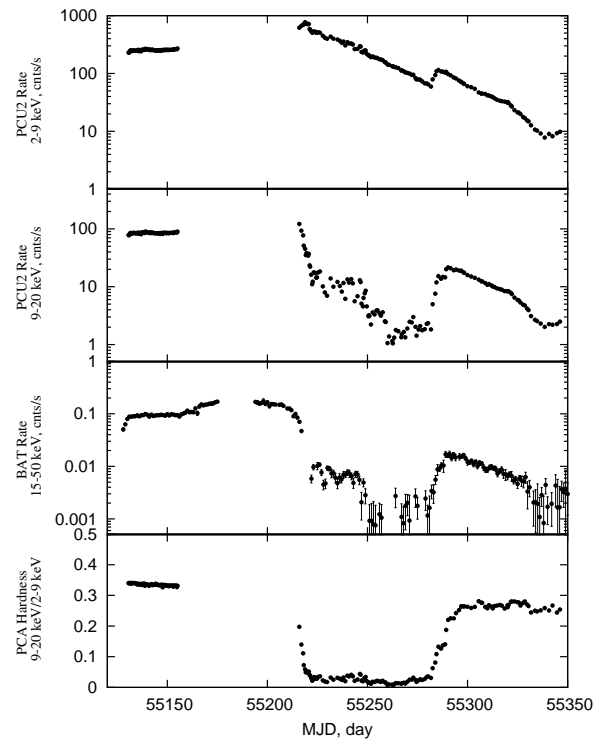


Figure 1. *RXTE* and *Swift* lightcurves calculated for various energy ranges.

On October 23, 2009 17:52 UT *RXTE* performed a routine scan of the Galactic bulge using the Proportional Counter Array (PCA). The scan analysis showed residuals consistent with a new source at the position RA = 268.05 ± 0.08 , DEC = -22.31 ± 0.02 (J2000 coordinate system). Search for fast time variability yielded no significant pulsations. On October 24, 2009 *Swift* BAT instrument triggered on the source and determined a position consistent with the PCA error circle (Markwardt et al. 2009a). On October 25, 06:08 UT *Swift* performed a dedicated follow-up observation, which confirmed the previously determined source position and allowed to estimate an interstellar extinction toward the source of $N_H = 0.46 \times 10^{-22} \text{ cm}^{-2}$. The observation also revealed a very hard non-thermal spectrum with a power law index of 1.2 (Markwardt et al. 2009b). On October 26, 15:03 UT *RXTE* was able to make its first pointed observation of XTE J1752-223. Overall spectral and timing properties are strongly reminiscent of the extreme low-hard states exhibited by Cyg X-1 and GX 339-4, which prompted a preliminary classification of the source as a BH candidate (Shaposhnikov et al. 2009). Following this identification we triggered our *RXTE* Cycle 14 TOO observations for frequent monitoring of BH transient X-ray sources. This program revealed source evolution completely consistent with the source being a BH candidate. Namely, the source exhibited typical black hole spectral states, accompanied with corresponding fast variability properties. As described below, this monitoring completely confirmed our expectations and showed source evolution and state transitions consistent with the current observational scenario of classical accreting BH in outburst. Specifically, XTE J1752-223 went through the initial LHS, transitioned through IS to HSS, returned to LHS and decayed to quiescence. The

very high state, sometimes called the steep power law state (Remillard & McClintock 2006), which occurs for the most luminous BH transients, was not observed. The nature of the central compact object in XTE J1752-223 as a BH is also strongly supported by BH mass estimate presented in §6, which strongly favors the mass range of 8-11 M_{\odot} .

3. RXTE OBSERVATIONS AND DATA ANALYSIS

We have analyzed 195 pointed *RXTE*/PCA observations beginning on October 26 2009, 14:24 UT (MJD 55130.6) and ending on April 20, 2010 22:48 UT (MJD 55306.95). For the period of two months beginning from November, 20 2009 until January 19, 2010 XTE J1752-223 was not available for *RXTE* pointed observations due to the Sun constraint. *Swift*/BAT also was not able to observe the source for approximately a month within this period. While the source showed some activity after April 20, 2010, we do not include *RXTE* observations after this date in our analysis as the PCA data is dominated by the Galactic ridge emission. For spectral analysis we utilized data collected with the PCU 2 top layer only. We extracted spectra from Standard2 mode data files which provide spectra in 129 channels. The PCA response was calculated using the FTOOL *pcarmf 11.7*. Spectra were deadtime corrected according to "RXTE Cookbook"⁴. The PCA background was estimated using FTOOL task *pcabackest*. For spectral analysis the background was scaled to match the detected counts in Standard2 channels above 110 corresponding to energies above 75 keV, where no significant source signal is expected.

We extracted the background subtracted *RXTE*/PCA count rates in energy bands 2-9, 9-20 and 20-50 keV. *RXTE* and *Swift*/BAT lightcurves along with the hardness ratio are presented in Figure 1. The *Swift*/BAT data is provided by the *Swift*/BAT team.

PCA spectra were analyzed in the energy range from 3.0 to 45.0 keV. To model the spectra we apply the model consisting of the generic Comptonization model (BMC XSPEC model; Titarchuk et al. 1997) plus a *gaussian* for the iron emission line at 6.4 keV, modified by the interstellar absorption with N_H fixed at $0.46 \times 10^{22} \text{ cm}^{-2}$ (Markwardt et al. 2009b). The main component of our spectral model was initially introduced to treat spectra produced by boosting thermal disk photons in the convergent inflows near the central BH where bulk motion is dominant in upscattering, hence the name BMC (Bulk Motion Comptonization). The model employs the Green function convolution technique to convert a part of the input black-body spectrum to the power law component. Designed in this way the BMC model is applicable to any upscattering process which can be described by a broken power-law Green function and is applicable to the Comptonization on thermal electrons. The parameters of the BMC model are the temperature of the input black-body spectrum kT , its normalization N in units of $(L/10^{39} \text{ erg/s})(10 \text{ kpc}/d)^2$, the Comptonized fraction f (implemented as a $\log(A)$ parameter, where $f = A/(1 + A)$) and the photon index $\alpha = \Gamma - 1$ of the power law tail. The BMC model does not account for the electron recoil during Comptonization as the recoil effect

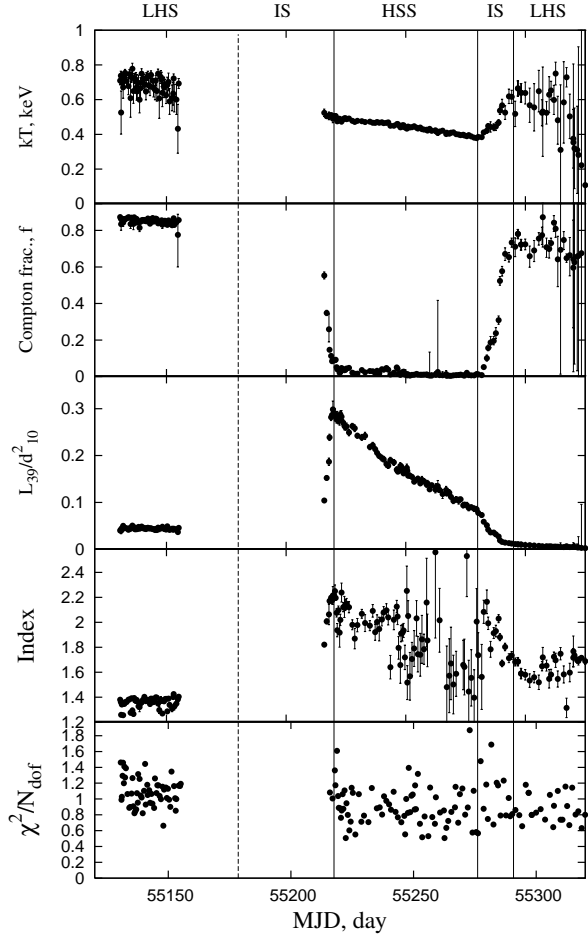


Figure 2. Evolution of XTE J1752-223 spectral parameters throughout the outburst inferred for individual *RXTE*/PCA pointing observations. The labels at the top show the corresponding spectral state of the source. The boundary between initial the LHS and the IS is shown approximately as no information is available due to the Sun occultation.

strongly depends on a particular Comptonization regime and is not trivial to treat analytically. It therefore has to be modeled phenomenologically by adding the high energy cutoff to X-ray spectra. During the LHS the high energy cutoff above ~ 20 keV was added to the model as required by the data. Evolution of spectral parameters of the Comptonization model are given in Figure 2. The analysis was done in XSPEC 12.0 analysis package.

For timing analysis we constructed Fourier power density spectra (PDS) for each observation in the frequency range from 0.01 Hz to 512 Hz using the *powspec* FTOOL task. To calculate the PDS we combined counts from the whole PCA energy range using high resolution data modes. PDS are normalized to units of fractional squared root-mean-square (RMS) per Hz. We apply deadtime correction to PDS spectra according to Zhang et al. (1995). Total RMS values were then calculated as the square root of the integrated power in the frequency range from 0.01 Hz to 100 Hz. To investigate the energy distribution of the RMS (RMS spectrum) we first calculated spectra from the event or binned PCA modes

⁴ http://heasarc.gsfc.nasa.gov/docs/xte/recipes/cook_book.html

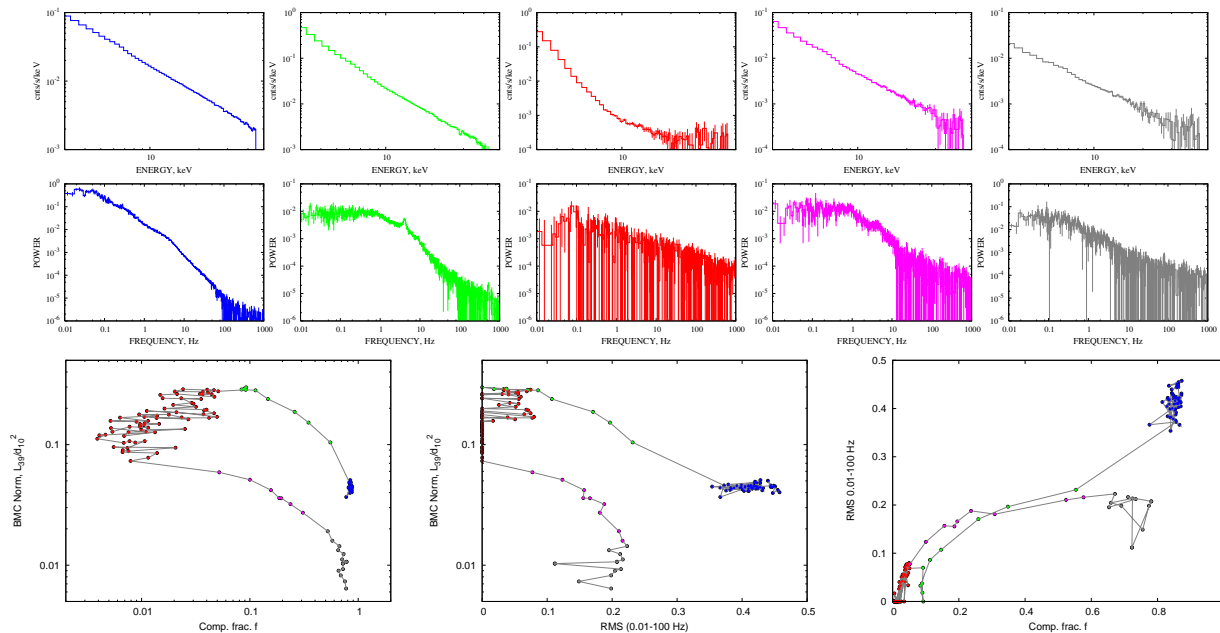


Figure 3. Correlation of spectra and variability in XTE J1752-223 during the reported outburst. Representative energy spectra are shown in the top panels, while the power density spectra are presented in the second row. In the bottom row the hardness-intensity, hardness-rms and rms-flux correlations are shown. The colors correspond to spectral states as follows: blue for the initial LHS, green for the rise IS, red for the HSS, magenta for the decay IS and grey for the decay LHS. The specific RXTE observation used for the energy and power spectra are: 94044-07-01-000 for the initial LHS, 94331-01-06-01 for the rise IS, 95360-01-05-04 for the HSS, 95360-01-11-01 for the decay IS and 95702-01-01-00 for the decay LHS.

and normalized the spectral bins with the RMS values calculated for each bin, thus obtaining the spectrum of the variable part of the emission. The RMS spectrum is then obtained as a ratio of the variable spectrum to the spectral model for the total spectrum, obtained as described in the previous paragraph.

4. EVOLUTION OF XTE J1752-223

In Figure 1 we present *RXTE*/PCA and *Swift*/BAT lightcurves in various energy bands as well as PCA hardness. The outburst started in the LHS, which lasted from MJD 55130 to approximately MJD 55200. The PDS was represented by a flat-top broken power law shape with a break at 0.18 Hz and total root-mean-square variability of 45%.

As indicated by the *Swift*/BAT lightcurve, beginning on MJD 55155 the source started to evolve towards the IS (see also Curran et al. 2010, for detailed analysis of *Swift* data). *RXTE* observations were interrupted by Sun constraints until MJD 55215. More coverage was provided by *Swift*/BAT monitoring, which was also not able to observe from MJD 55175 to MJD 55194. For this reasons, it is hard to identify precisely the time when the source entered the IS. We can only speculate that it most probably occurred around MJD 55200, when a turnover in 15-20 keV *Swift*/BAT flux is observed.

RXTE monitoring resumed on MJD 55215.9 (19 Jan 2010 21:36 UT), when the source was found to be in the fast transition phase. The first *RXTE* pointed observation after interruption revealed a spectrum with a much softer power law component ($\Gamma = 1.8$) and more pronounced disk black body part, which is consistent with the hard IS (HIMS) spectral state. The aperiodic PDS component had a break at 0.5 Hz and rms variability of 25%. It was accompanied by a clear Type-C QPO (Casella et al. 2005) at 2.2 Hz (Shaposhnikov

2010). Type-C QPOs were also observed during two following observations on MJD 55216.9 (20 Jan 2010 21:36 UT) and 55217.9 (21 Jan 2010 21:30 UT) at 4.1 Hz and 5.3 Hz correspondingly, while the total rms variability decreased from 25% to 18%. Near the end of the IS on MJD 55218 and 55220 Type A/B QPO were observed during observations 95360-01-01-00 and 95360-01-01-02. These observations are consistent with a soft IS (SIMS). After that the source entered the HSS. Some broad-band variability was observed at the level of several percent through the first half of the HSS until MJD 55245. After that and until the start of the decay stage IS the PDS from XTE J1752-223 was featureless and consistent with zero variability above 0.01 Hz. It is interesting to note that the first part of the HSS when the variability was present corresponds to the period of significant hard X-ray flux in the energy range excluding the contribution from the thermal disk-black body component, i.e. 9-20 keV range for *RXTE*/PCA and 15-50 keV for *Swift*/BAT (see Figure 1). During the second non-variable part of the HSS the hard fluxes shown by both *RXTE* and *Swift* are close to the background level. Presence of significant non-thermal emission during the first half of the HSS is also indicated by the Comptonization factor f in Figure 2. Namely, during the first “noisy” part of the HSS f is between 3 and 6 percent, the second “quiet” half of the HSS is Comptonized at $\sim 2\%$ only.

The source X-ray flux showed a gradual decline throughout the HSS, as indicated by count rates in different channel ranges and the spectral model normalization. On MJD 55282.56 (27 March 2010 13:25 UT), after more than 100 days in the HSS, the system exhibited a sudden increase in flux, both in soft and hard energy ranges, such that the source hardness increased. In addition, the aperiodic variability reappeared at the

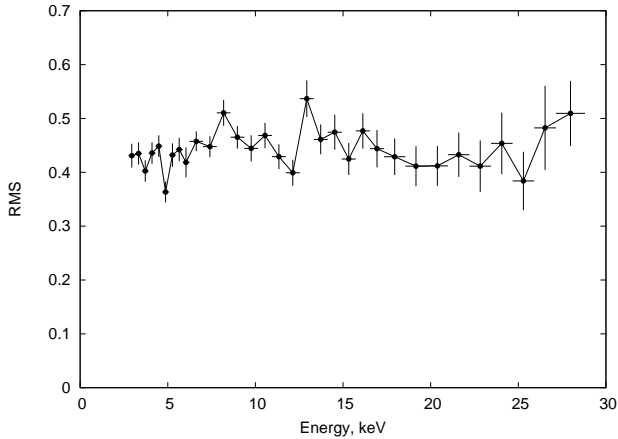


Figure 4. RMS spectrum in XTE J1752-223 during the LHS (Observation 94331-01-05-00).

level of 8% rms, indicating that the system was in the IS (Muñoz Darías et al. 2010). The decay stage IS lasted for approximately two weeks during which the Comptonized fraction f increased from below 0.02 to ~ 0.7 and the power law index decreased from 2.0 to 1.6. The LHS was reached around April 4, 2010 (MJD 55295). The variability increased to 0.2-0.25 rms represented by the flat-top noise with a hint of a broad QPO.

At the top of Figure 3 we show representative energy spectra and the PDS for each stage of the outburst. Each data point is shown in color according to its spectral state, i.e. blue for the initial LHS, green for the first IS, red for the HSS, magenta for the second IS and cyan for the decay LHS. The bottom diagrams show three correlation plots between essential spectral and variability characteristics. On the left panel we present the spectrum normalization N versus Comptonized fraction f on the log-log scale. On the middle diagram the N –rms correlation is shown and the right panel presents the rms– f correlation. As can be seen from the form of the correlation pattern, the N – f correlation is a Comptonization model analog of the famous q-shaped hardness-intensity diagram (see Belloni 2010, and references therein). Both N – f and N –RMS correlations show a strong hysteresis effect when the initial hard-to-soft spectral state transition occurs at higher luminosity than the decay soft-to-hard transition (Meyer-Hofmeister et al. 2005). The hysteresis effect is also seen in the RMS– f plot. We discuss the evolution of the source through different spectral states in §7.

5. XTE J1752-223 RMS SPECTRUM

As noted by Muñoz-Darías et al. (2010), analysis of the *RXTE* data during the beginning of LHS stage in XTE J1752-223 showed no energy dependence of the variability versus energy. We note, however, that according to analysis of *Swift* data by Curran et al. (2010), the uniformity in RMS amplitudes versus energy breaks down for energies below 1.5 keV as the variability shown by XRT data is above 50% during the LHS. In Figure 4 we show the rms spectrum for the last *RXTE* observation during the LHS stage made on before the source became unobservable due to Sun constraint. Despite some scatter in RMS values the variability is practically constant in en-

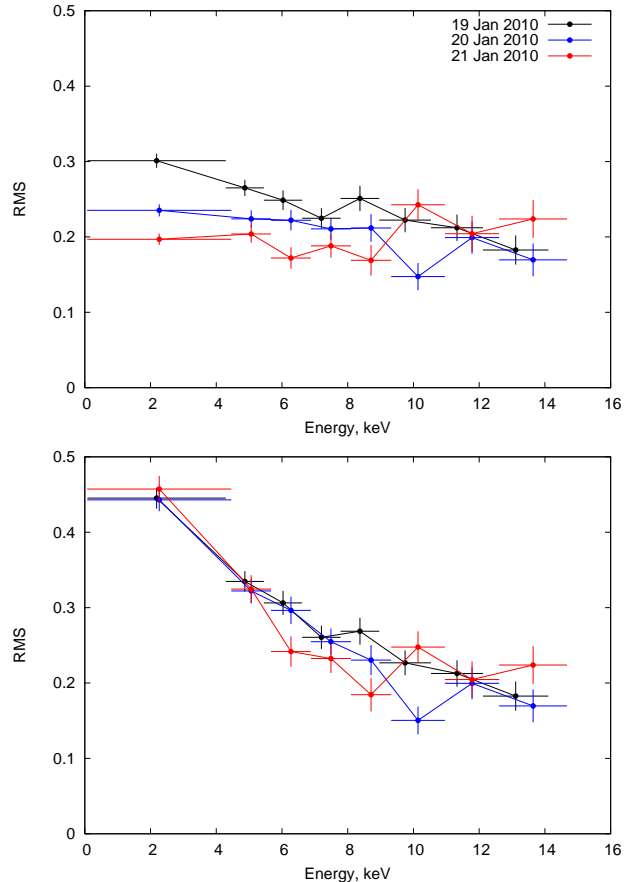


Figure 5. *Top:* Distributions of the fractional root-mean-square variability with energy for three observations during the spectral transition when a Type-C QPO was observed (the hard IS). The RMS is normalized by the total spectral model including both thermal and power law components (see text). *Bottom:* The same as above but for RMS normalized by the power law component only.

ergy, at the level of ~ 0.45 rms. However, the situation changes considerably during the IS. In Figure 5 we show the rms energy distribution for the first three observations in the IS, when Type-C QPOs were observed. The top panel shows the fractional RMS values calculated in the conventional sense, i.e. the rms is normalized by a total source spectrum. It is clearly seen that rms values for energies below 10 keV are gradually decreasing from 0.3 to 0.2 RMS, while the variability level for the higher energies is stable at the level of ~ 0.2 . This decrease in variability is closely correlated with the corresponding increase in contribution of the thermal “black-body” spectral component in the lower energy range. This suggests that the intrinsic variability of the thermal component is much less than that in the power law component. This is consistent with the previous claims of stability of the accretion disk emission (Churazov et al. 2001; Homan et al. 2001; Życki et al. 2007).

Among the observational facts which indicate that fast variability in XTE J1752-223 is concentrated towards (if not entirely confined within) the non-thermal part of the spectrum are (a) very high variability in the LHS, (b) non-detection of the variability in the second half of the HSS, when the Comptonization factor f is less than 3%, and (c) tight correlations between f and rms (Figure 3, right panel in the bottom). It is therefore more

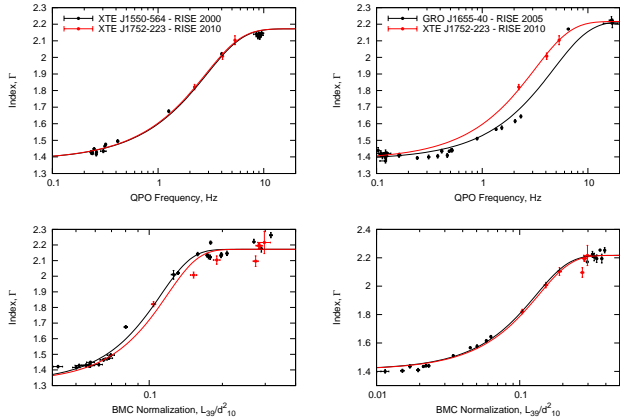


Figure 6. Correlation scaling of the state transition data for XTE J1752-223, presented by black points, versus GRO J1655-40 (left panel) and XTE J1550-564 (right panel). Data for reference sources are shown in red. Top panels show scaling index-QPO frequency curves, while at the bottom we show Index vs spectrum normalization data.

informative and natural to consider the rms variability level with respect to the power law emission component only. The rms spectra calculated with respect to the non-thermal spectral component (i.e. with the black body and Gaussian components excluded) are shown in the bottom panel of Figure 5. We first note the remarkable similarity of the power-law normalized rms spectra for all three data sets. This fact shows that, if the variability is indeed concentrated in the power law component, the rms energy distribution remains fairly constant during the considered part of the IS. The second notable result is that the highest level of variability is observed for the lowest energy ~ 3 keV and is the same that the variability observed during the LHS, i.e. about 0.45. The third fact to mention is the gradual decrease in rms with energy. These facts have strong implications for the scenarios of the non-thermal emission production in BH X-ray binaries, as discuss in §7.

6. BH MASS AND THE DISTANCE TO XTE J1752-223

BH mass and distance measurements from X-ray spectral and fast variability analysis data require the following data and information. First, we need a reference source for which the BH mass and distance are known. For the reference and the target (the source for which the fundamental parameters are to be determined) we need scalable and well sampled observations of timing and spectral evolution through spectral transitions. The scaling factors are calculated between the spectral index - QPO frequency and index - normalization correlation patterns, which is achieved usually by fitting an empirical analytical function to the data. While the QPO frequency depends on the BH mass ratio only, the normalization ratio is a function of the masses and distances and also contains a factor depending on inclination angles. This geometrical factor is very close to unity in most cases (see ST09 for details).

As mentioned above, *RXTE* was not able to observe an entire hard-to-soft transition episode. QPOs were detected for three observations only. These data, however, provide enough information to test scalability and calculate scale coefficients in the index-QPO domain. The index-normalization data allow more reliable examina-

tion of the patterns self-similarity. To apply the scaling method for BH mass and distance measurement in XTE J1752-223 we use data from LHS-HSS transitions in two BH candidates GRO J1655-40 (2005 outburst) and XTE J1550-564 (2000 outburst) for which independent information on the BH mass and distance is available. These transitions were analyzed in ST09. Both data sets show correlation patterns scalable to the XTE J1752-223 transition behavior. We fit the reference correlation patterns with the analytical function discussed in ST09 and then calculate the scaling coefficient by refitting the functional shape to the target source data using transform $x \rightarrow sx$, where x is a x-axis argument and s is a corresponding scaling coefficient. The data and the approximating functions used for scaling are shown in Figure 6. The resulting values of the scaling coefficients and the final values of BH mass and distance for XTE J1752-223 are given in Table 1. The BH mass and distance values are calculated and errors for all parameters are propagated according to formulas $M_t = s_\nu M_s$ and $d_t = (s_\nu s_n)^{1/2} d_r$ (assuming the unity geometrical factor f_G , see ST09), where the subscript t stands for the target source (i.e. XTE J1752-223) and r is for the reference source (i.e. GRO J1655-40 or XTE J1550-564). All errors represent 1σ confidence parameter ranges. Both scalings based on the independently determined reference values give markedly consistent results for both BH mass and the source distance. We conclude that the BH mass in XTE J1752-223 is $M_{XTEJ1752-223} = 9.6 \pm 0.9 M_\odot$, while the distance is $d_{XTEJ1752-223} = 3.5 \pm 0.4$ kpc, which are obtained by averaging the results of scaling to GRO J1655-40 and XTE J1550-564.

The agreement of our double validation for the obtained BH mass and distance is rather convincing. We note, however, that the hard-to-soft transition that we use for our calculations was not fully sampled due the Sun constraints. We also note that for the 2005 transition in GRO J1655-40 one data point falls off the main ν_{QPO} -index correlation track. This observation (*RXTE* ObsID 91702-01-02-00G) was performed during a quick flare, when the source was undergoing fast changes in its spectral and variability properties (see Shaposhnikov et al. 2007). Therefore, the measurements of QPO frequency and spectral index may be biased during this observation. Nevertheless, we include the data point for this observation in the scaling procedure for consistency with previous analyses. Optical monitoring holds promise for dynamical mass determination (Torres et al. 2009a). Pending such a confirmation, some caution is recommended when interpreting the above results.

7. DISCUSSION

Let us summarize the main results of our observations and analysis. During the reported discovery outburst a new galactic BH candidate source XTE J1752-223 has shown behavior completely consistent with the general pattern of previously observed outbursts from BH X-ray binaries. It has evolved through BH spectral states, showing the expected corresponding changes in variability.

The characteristic extreme LHS was observed in the beginning of the outburst. This state was seen in many galactic BH transients during the outburst initial phase. In most cases the source evolves quickly to

Table 1
BH Mass and Distance Measurement in XTE J1752-223

Reference Source BH mass and Distance ^a	Scaling Coefficients	XTE J1752-223 BH mass and distance ^b
GRO J1655-40		
$M_{1655} = 6.3 \pm 0.5$ (1)	$s_\nu = 1.50 \pm 0.04$	$M_{1752} = 9.4 \pm 1.0$
$d_{1655} = 3.2 \pm 0.2$ (2)	$s_N = 0.96 \pm 0.05$	$d_{1752} = 3.8 \pm 0.4$
XTE J550-564		
$M_{1550} = 9.5 \pm 1.1$ (3)	$s_\nu = 1.03 \pm 0.03$	$M_{1752} = 9.8 \pm 1.4$
$M_{1550} = 3.3 \pm 0.5$ (4)	$s_N = 0.94 \pm 0.05$	$d_{1752} = 3.2 \pm 0.7$

^a $m = M/M_\odot$, distance d is given in kiloparsecs

References - ¹ Greene et al. (2001), ² Hjellming & Rupen (1995),

³ Orosz et al. (2002), ⁴ ST09

wards softer states. However, the LHS in XTE J1752-223 lasted for 3 months, showing uniquely stable spectral and timing properties (see also Muñoz-Darias et al. 2010). Prolonged hard states have been seen in GX 339-4 (Belloni et al. 2006), XTE J1118+480 (Brocksopp et al. 2010) and Cygnus X-1 (Nowak et al. 1999). XTE J1118+480 never showed a transition to HSS while Cygnus X-1 is a persistent source. Therefore, the closest analogy is with GX 339-4. The duration of the LHS phase may be related to the time delay between the initial mass injection by a donor star into the Roche lobe and the time for the thin accretion disk to form and to reach the inner accretion flow zone and to trigger a state transition. The gas with high angular momentum has to form a thin disk in order to dispose excessive momentum before being accreted. On the other hand, accretion of the low momentum gas occurs in the non-keplerian regime and the matter reaches the compact object much faster.

The emission during the LHS is quite variable with a fractional RMS of 43-48%. In Figure 4 we show the RMS spectrum during the last LHS observation on November 20 2:24 UT (ObsID 94331-01-05-00). The distribution is uniform over the energy range from 3 to 30 keV. However, during the state transition the rms spectrum changes considerably. As the source evolves towards the HSS, the overall RMS level drops. At the later stages of the IS, which were observed by *RXTE*, the drop in the variability amplitude is consistent with the increase in the soft thermal component due to an accretion disk as shown in §5. In fact, we find evidence that the entire variability is contained within the power law spectral component. When we normalize the RMS spectrum by the non-thermal part of the spectrum the RMS energy distribution is non-uniform with the RMS amplitude decreasing with energy. This fact may be related to the physics of photon upscattering. Motta et al. (2009) pointed out the evolution pattern of the high energy cutoff of the energy spectrum during the state transition shown by GX 339-4 during the 2007 outburst. The authors observed a decrease in the cutoff energy during the first part of the transition (hard IS) from about 150 keV to 50 keV and then an abrupt cutoff increase during the second part of the transition (soft IS), which was also accompanied by changes in timing behavior. Titarchuk & Shaposhnikov (2010) have recently identified the same effect in the galactic BHC XTE J1550-564 and interpreted it as a manifestation of a gradual change in the photon upscattering regime from pure thermal to bulk motion Comptonization (Titarchuk et al. 1997).

The evolution of the rms spectrum shown by XTE J1752-223 during the hard-to-soft state transition can also be interpreted in terms of this scenario. During the LHS Comptonization is purely thermal. Photons detected at all energies are upscattered by the same hot turbulent plasma resulting in a uniform distribution in rms amplitudes versus energy (see Figure 4). As the source moves towards the softer states, emission from an advancing accretion disk effectively cools the Compton corona causing its contraction and exposing the innermost region of the accretion flow to the observer, where bulk motion is the dominant process for photon upscattering. Therefore, the gradual collapse of the thermal corona leads to the increasing contribution of the bulk motion Comptonization as an upscattering agent for the emerging non-thermal radiation. The bulk motion contribution in upscattering should also be higher for the photons emerging at higher energies. If we assume that the variability is mostly produced by perturbations in the thermal Comptonization region and the bulk motion region is much more stable, the observed RMS decline with energy seen in Figure 5 finds a natural explanation. Namely, the higher energy emission is less variable as the photons are boosted in the less variable bulk motion region. It is also clear that the soft photons at about 3 keV which belong to the power spectral component are produced by the thermal Comptonization as revealed by the corresponding variability of $\sim 45\%$ consistent with RMS level of the LHS. Further investigation of the RMS spectra evolution along these lines seems to be very promising. We will pursue this to verify the RMS behavior observed in XTE J1752-223 in other galactic BH sources.

8. CONCLUSIONS

XTE J1752-223 is a new galactic BH candidate. During the 2009-2010 discovery outburst the source evolved from the extreme LHS to HSS through IS as observed by *RXTE* extensive monitoring program. We studied the evolution of spectral and timing properties of the source during the the outburst using available *RXTE* data, specifically concentrating on the transition phase, when the source exhibited low-frequency QPOs. Evolution of the RMS variability throughout the outburst and the behavior of the RMS spectrum during the state transition suggest the non-thermal part of the energy spectrum as a primary source of the flux modulation. QPO frequency and spectrum normalization evolution, when compared to the transition data from 2005 outburst of GRO J1655-40 and 2000 outburst of XTE J1550-564, strongly indicates that BH mass in XTE J1752-223 is 9.6 ± 0.9 solar masses. We estimate the distance to the source in the range of 3.5 ± 0.4 kpc. This result confirms the expectation that the compact object in XTE J1752-223 is a stellar mass BH.

We made use of the data provided through HEASARC and *RXTE* SOF. NS acknowledge the support of this work by NASA grant NNX09AF02G.

REFERENCES

- Belloni, T., Homan, J., Casella, P., van der Klis, M., Nespoli, E., Lewin, W. H. G., Miller, J. M., & Méndez, M. 2005, *A&A*, 440, 207

- Belloni, T. 2005, *Interacting Binaries: Accretion, Evolution, and Outcomes*, 797, 197
- Belloni, T., et al. 2006, *MNRAS*, 367, 1113
- Belloni, T. M. 2010, *Lecture Notes in Physics*, Berlin Springer Verlag, 794, 53
- Brocksopp, C., Jonker, P. G., Maitra, D., Krimm, H. A., Pooley, G. G., Ramsay, G., & Zurita, C. 2010, *MNRAS*, 404, 908
- Casella, P., Belloni, T., & Stella, L. 2005, *ApJ*, 629, 403
- Churazov, E., Gilfanov, M., & Revnivtsev, M. 2001, *MNRAS*, 321, 759
- Curran, P. A., Maccarone, T. J., Casella, P., Evans, P. A., Landsman, W., Krimm, H. A., Brocksopp, C., & Still, M. 2010, *arXiv:1007.5430*
- Greene, J., Bailyn, C. D., & Orosz, J. A. 2001, *ApJ*, 554, 1290
- Hjellming, R. M., & Rupen, M. P. 1995, *Nature*, 375, 464
- Homan, J., Wijnands, R., van der Klis, M., Belloni, T., van Paradijs, J., Klein-Wolt, M., Fender, R., & Méndez, M. 2001, *ApJS*, 132, 377
- Homan, J., Wijnands, R., Kong, A., Miller, J. M., Rossi, S., Belloni, T., & Lewin, W. H. G. 2006, *MNRAS*, 366, 235
- Markwardt, C. B., et al. 2009, *The Astronomer's Telegram*, 2258, 1
- Markwardt, C. B., Barthelmy, S. D., Evans, P. A., & Swank, J. H. 2009, *The Astronomer's Telegram*, 2261, 1
- Meyer-Hofmeister, E., Liu, B. F., & Meyer, F. 2005, *A&A*, 432, 181
- Motta, S., Belloni, T., & Homan, J. 2009, *MNRAS*, 400, 1603
- Muñoz-Darias, T., Motta, S., Pawar, D., Belloni, T. M., Campana, S., & Bhattacharya, D. 2010, *MNRAS*, 404, L94
- Muñoz Darias, T., Motta, S., Belloni, T., & Homan, J. 2010, *The Astronomer's Telegram*, 2518, 1
- Nowak, M. A., Vaughan, B. A., Wilms, J., Dove, J. B., & Begelman, M. C. 1999, *ApJ*, 510, 874
- Orosz, J. A., et al. 2002, *ApJ*, 568, 845
- Remillard, R. A., & McClintock, J. E. 2006, *ARA&A*, 44, 49
- Shaposhnikov, N., & Titarchuk, L. 2006, *ApJ*, 643, 1098
- Shaposhnikov, N., Swank, J., Shrader, C. R., Rupen, M., Beckmann, V., Markwardt, C. B., & Smith, D. A. 2007, *ApJ*, 655, 434
- Shaposhnikov, N., & Titarchuk, L. 2009, *ApJ*, 699, 453 (ST09)
- Shaposhnikov, N., Markwardt, C. B., & Swank, J. H. 2009, *The Astronomer's Telegram*, 2269, 1
- Shaposhnikov, N. 2010, *The Astronomer's Telegram*, 2391, 1
- Titarchuk, L., Mastichiadis, A., & Kylafis, N. D., 1997, *ApJ*, 487, 834
- Titarchuk, L. & Shaposhnikov, N., 2010, *ApJ*, in press
- Torres, M. A. P., Jonker, P. G., Steeghs, D., Yan, H., Huang, J., & Soderberg, A. M. 2009, *The Astronomer's Telegram*, 2263, 1
- Torres, M. A. P., Steeghs, D., Jonker, P. G., Thompson, I., & Soderberg, A. M. 2009, *The Astronomer's Telegram*, 2268, 1
- Zhang, W., Jahoda, K., Swank, J. H., Morgan, E. H., & Giles, A. B. 1995, *ApJ*, 449, 930
- Życki, P. T., Sobolewska, M. A., & Niedzwiecki, A. 2007, *IAU Symposium*, 238, 13